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Linear Class B Audio Amplifier Output-Power Capability

Analysis of Load-Impedance and Waveform Effects

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CONTENTS

ABSTRACT

Large amounts of electrical power at audio frequency are usually provided by some form of class B electronic amplifier. Unfortunately, changes in load impedance and in waveform can result in very large reductions in the output-power capability of such amplifiers.

The design equations for class B amplifiers are developed with respect to impedance and signal waveshape. Manipulation of the equations leads to proof that class B amplifier operation with any signal waveshape can be assumed to be the same as operation with a sine wave of the same root-mean-square value. Therefore, once the sine-wave capability of a class B amplifier is determined, its capability for other waveshapes is determined by application of a simple derived multiplication factor.

The sine-wave capability of class B amplifiers has been determined and presented in the form of graphs of power versus magnitude of impedance for fixed power factors and device peak-voltage capabilities.

In general, the optimum sine-wave-output capability is determined as the power-dissipation capability of each device multiplied by 4.93, provided the current limit is not exceeded. The actual output capability will be reduced in magnitude by load and signal effects and system efficiency. This reduction is of the order of ten for loads with power factor of 0.7 and impedance swing of 4:1 and for device efficiency of 70 percent and circuit efficiency of 92 percent.

For signals other than sine waves, the sine-wave average-power capability is then further reduced and is determined, in the worst case, by multiplying the sine-wave capacity by two and dividing by the square of the crest factor.

PROBLEM STATUS

This is an interim report on one phase of the project; work on this problem is continuing.

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LINEAR CLASS B AUDIO AMPLIFIER OUTPUT-POWER CAPABILITY

ANALYSIS OF LOAD-IMPEDANCE AND WAVEFORM EFFECTS

INTRODUCTION

A requirement for large amounts of electrical power at audio frequencies is usually met by using some form of class B electronic amplifier having either vacuum tubes or transistors for active devices. The design procedure for such amplifiers is relatively simple, straightforward, and well known. There are, however, some unusual and possibly unexpected factors in the design with regard to the power-output capability as a function of changing load impedances and/or waveforms other than sinusoids. Either or both of these conditions are generally present when sonar-transducer loads are being used, and may be present in other applications.

The changes in the expected nominal or design-center value of the power-output capability resulting from these factors can be, unfortunately, quite large and are usually in the direction of reduced capability. It is necessary, therefore, to develop procedures to determine the magnitude of these changes if intelligent application of class B power amplifiers is to be made. Such procedures, applicable to amplifiers using either tubes or transistors, are developed in this report.

LINEAR CLASS B AMPLIFIER PRINCIPLES

In general, the design emphasis in class B linear amplifiers is in the area of the output-power capability. The power capability is determined primarily by three parameters of the active devices used; namely, the maximum voltage, the maximum current, and the maximum power dissipation. This is true whether the amplifier is a transformer-coupled vacuum-tube system, one of several transformerless transistor systems, or a transformer-coupled transistor system.

The maximum power-dissipation capability of any active device is a function of the available cooling medium and the duty cycle of the operation. Before this parameter is applied in determining the output-power capability, therefore, the general operating characteristics of the system will be determined.

If one assumes that infinite cooling is available, then the maximum output-power capability is determined from the voltage and current ratings of the active devices. In class B amplifiers, where large-signal conditions are the rule, the design is usually based on the output-characteristic curves supplied by the manufacturer, rather than on equivalent circuits. These curves take the two familiar forms of the triode vacuum-tube characteristic (Fig. 1), and the pentode or beam-power tetrode vacuum-tube characteristic (Fig. 2a), or the transistor characteristic (Fig. 2b). For the purposes of this analysis, the difference in these characteristics is the voltage drop in the device. The detailed results and figures in this analysis are primarily applicable to pentodes and transistors, but the formulae are applicable to any linear device.

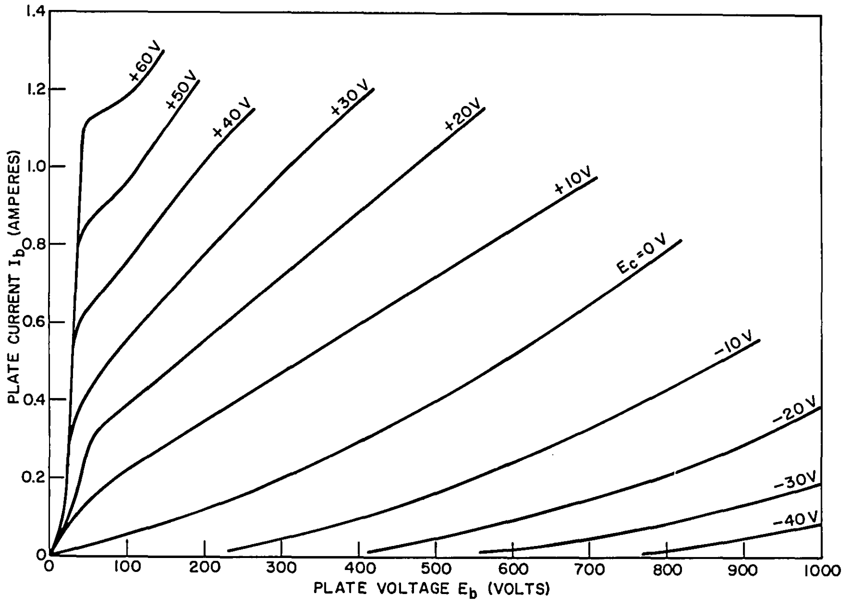
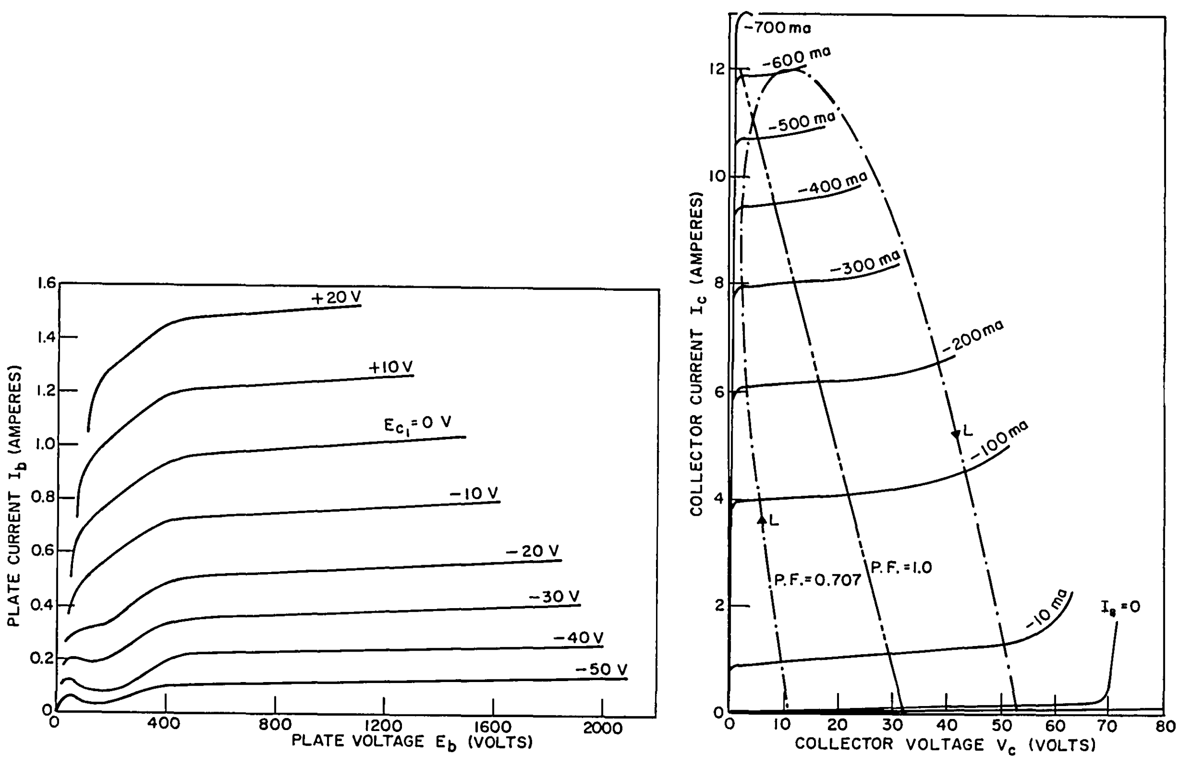


Fig. 1 - Output characteristics, power triode (5588)



(a) Beam-power tube (7094)

(b) Transistor (2N2492)

Fig. 2 - Constant-current output characteristics

The first step in a power-output-capability analysis is to determine the dc-supply voltage from the maximum-voltage rating of the device. In many class B amplifier configurations, the maximum voltage is sustained during the period of no current conduction and is twice the dc-supply voltage. The selected dc voltage would be, in these cases, one-half the maximum device voltage, less an amount ranging from 10 to 50 percent of the device rating, depending on the reliability desired, for a safety factor.

In any case, the required load resistance load-line is drawn between the dc-supply voltage and the maximum device-current rating (Fig. 2b). The device-to-ground resistance thus determined is given by the equation:

$$R_{DG} = \frac{E_B - E_D}{I_D}, \tag{1}$$

where

E_B is the dc-supply voltage

E_D is the device-voltage drop

I_D is the device current at E_D.

The resistive load line (Fig. 2b) is also the axis of the distorted ellipse or circle resulting from actual loads other than a pure resistance. Equation (1) then gives the magnitude of the impedance.

The maximum undistorted power which is obtainable for any waveform is given by the equation:

$$P_{om} = \frac{(E_B - E_D)I_D}{C_E C_I} \cos\theta_z, \tag{2}$$

where

C_E and C_I are the crest factors or peak-to-rms ratios of the voltage and current waveforms, respectively

$\cos\theta_z$ is the power factor of the actual load impedance.

For the specific case of resistive loads and sine waves ($C_E = C_I = 1.414$), Eq. (2) reduces to the usual form:

$$P_{om} = \frac{(E_B - E_D)I_D}{2}. \tag{3}$$

Since the maximum peak voltage, E_{pk}, is $(E_B - E_D)$, and since the maximum peak current, I_{pk}, is I_D, Eqs. (2) and (3) can be generalized to any output level, P_o, by substitution of E_{pk} and I_{pk}.

The required dc-input power is determined from the fixed dc-supply voltage and the dc level of the output-current half wave. The ratio between the rms and the average values of a waveform is given by the form factor, F. The dc current can then be given as:

$$I_{dc} = \frac{I_{pk}}{C_I F}, \tag{4}$$

which reduces, for sine waves, to:

$$I_{dc} = 0.636 I_{pk}. \tag{5}$$

The dc-input power is the product of the current and the fixed supply voltage, and is given by:

$$P_i = \frac{E_B I_{pk}}{C_I F}, \tag{6}$$

where E_B is the dc-supply voltage. The power which must be dissipated in the active devices, the amplifier loss, is the difference between the input and output power (Eqs. (6) and (2)) and is given in the equation:

$$P_d = \frac{I_{pk}}{C_E C_I F}(C_E E_B - F E_{pk} \cos\theta_z). \tag{7}$$

Equation (7) reduces, for sine waves, to the form:

$$P_d = \frac{I_{pk}}{2.22}(1.414 E_B - 1.11 E_{pk} \cos\theta_z). \tag{8}$$

The efficiency is defined as the ratio of the output power to the input power, and is given by the equation:

$$\eta = \frac{F E_{pk} \cos\theta_z}{C_E E_B}, \tag{9}$$

which becomes, for sine waves:

$$\eta = \frac{0.785 E_{pk} \cos\theta_z}{E_B}. \tag{10}$$

It may be seen from Eqs. (9) or (10) that the operating efficiency of class B, linear power amplifiers is a linear function of the peak-output voltage. If one assumes pure class B operation with unity power-factor loads and sinusoidal waves, the relationship between the efficiency and the amplifier dissipation and output power, both normalized to the maximum theoretical output power, may be plotted as a function of the peak-voltage output, normalized to the dc-supply voltage (Fig. 3).* The same relationships may be plotted ($|Z| = R$) for several power factors other than unity (Figs 4 to 7). These figures show the increased losses and reduced output power and efficiency resulting from a reduction in power factor.

A class B, linear power amplifier, once a design has been fixed, is one which is capable of delivering a particular, fixed, maximum-output voltage which is a function of the device drop, and which will, in combination with the load, determine the output current. If clipping is not to be allowed (no change in crest factor), the maximum amplifier output is obtained when the peak-voltage capacity of the devices is reached. In any of these situations, the maximum dissipation will occur at 50-percent efficiency and will be at less than full signal output if the maximum-efficiency capability at full output power is greater than 50 percent.

SIGNAL CHARACTERISTICS

Design equations for class B amplifiers usually consider only sinusoidal signals. A sinusoidal signal, and any other waveform, can be characterized by its crest and form factors, which are, respectively, 1.414 and 1.11. All other types of waveforms, such as voice, music, noise, etc., will have their own characteristic factors.

A square wave, often used for frequency-response testing, has crest and form factors of unity. A triangular wave has a crest factor of 1.732 and a form factor of 1.155. Random noise is hard to characterize, but, in general, has crest factors greater than 3. Another

*Figures 3 through 17 are bound consecutively at the end of this report.

noise form of interest to sonar applications has crest factors of 4 to 6 and form factors of 1.1 to 1.4. Most forms of voice and music are characterized by high crest factors.

ANALYSIS OF THE EFFECT OF SIGNAL WAVEFORM ON OUTPUT POWER

Initially, in order to simplify the analysis, and because form factor does not enter into the output relationships, the form factor will be assumed to be constant at 1.11, and only the effect of crest factor will be considered. For the moment, only the case of unity power-factor loads will be considered.

As was discussed earlier, the maximum output will occur when the peak voltage is at its maximum possible value. The crest factor, C, of the current and voltage will be equal, and the maximum power output will be determined from Eq. (2). The equation can be modified to read:

$$P_{om} = K\left(\frac{1}{C}\right)^2, \tag{11}$$

where K is the peak-power product, and is a function of the particular devices used. For the case of sinusoidal signals, the general normalized power output can be expressed as:

$$P_o = K'\left(\frac{E_{pk}}{E_B}\right)^2, \tag{12}$$

where K' is equal to $1/(C^2R)$. From these two equations, it can be seen that the shape of the curve of maximum available power output as a function of crest factors increasing from the sine-wave value of 1.414 will be the same as the shape of the curve of general power output as a function of peak voltage decreasing from the maximum possible value of the supply voltage. If the relationship for maximum obtainable output power given by Eq. (11) is plotted with an abscissa equal to $1.414(1/C)$, the resulting graph will be identical to that obtained in Fig. 3 for the general power output as a function of the per-unit peak voltage.

Similar manipulation of Eq. (9) for efficiency will again result in two equations giving identically shaped curves. Again, if the equation for maximum obtainable efficiency is plotted as a function of $1.414(1/C)$, the resulting curve will be identical to the curve of efficiency versus per-unit peak voltage of Fig. 3.

Since the dissipation is a function of power output and efficiency:

$$P_d = P_o \left(\frac{1-\eta}{\eta}\right), \tag{13}$$

and, since both power output and efficiency in this case are identical to the curves of Fig. 3, it is obvious that the dissipation as a function of $(1/C)$ is the same as that for the operating dissipation shown in Fig. 3.

The discussion in the preceding two paragraphs means that, in order to characterize the operation of an amplifier with signals of crest factor greater than 1.414, one need only determine the maximum obtainable efficiency for that particular crest factor. The operation of the amplifier will then follow the sine-wave curves (Fig. 3) with maximum values of output power and dissipation corresponding to the particular maximum efficiency. Insofar as the amplifier operation is concerned, high-crest-factor waveshapes look the same as sine waves of the same rms value. A typical set of curves for a crest factor of 2.0 has been plotted in Fig. 8 to the scale of Fig. 3 on the basis of equal rms voltages. Such a plot results in a per-unit peak voltage of unity on Fig. 8 which is equal to $0.707E_{dc}$, the value for sine waves corresponding to the 55.5-percent maximum obtainable efficiency which can be obtained with a crest factor of 2.0.

Since power factor appears in the equations for power output and efficiency (Eqs. (2) and (9)) as a simple multiplication factor, operation with high-crest-factor signals on non-unity power-factor loads is, to a first approximation, the same as operation with reduced sine-wave signals, as previously discussed.

Operation of class B linear amplifiers with tuned loads and nonsinusoidal waves does not necessarily follow the above analysis, for the crest factor of the current and the voltage will probably be different. Such a difference will affect the output power even though no effect on efficiency may occur. For cases like this, it will be necessary to use Eqs. (2), (7), and (9). The general effect in these cases will be to increase the output power and reduce the dissipation. Thus, the preceding analysis is, in general, a worst-case analysis, and is quite useful.

Consideration of actual cases, where form factor does not stay constant at 1.11 but increases (generally true for increasing crest factors), again results in the preceding analysis being a worst-case analysis. Increasing form factor does not affect the output power but does increase the efficiency, and thus will reduce the dissipation.

The net result of this analysis of signal effects is that the signal can be ignored until the analysis of operation with varying load impedances has been completed, and may then be applied as a simple multiplication factor to the sine-wave output power determined from the load analysis. The resulting power level is the lowest maximum output power that will be obtained, and the dissipation will not exceed the maximum rating of the devices. The factor by which the sine-wave power, determined from the load analysis, is to be multiplied is plotted in Fig. 9 for crest factors from 1 to 45. The factor from this figure can be applied to Figs. 3 to 7, but will be more applicable to subsequent figures.

ANALYSIS OF THE EFFECT OF LOAD IMPEDANCE ON OUTPUT POWER

The two parameters which must be considered when analyzing the effect of load impedance on class B amplifier operation are the magnitude and the phase angle as expressed by the power factor. Both of these parameters can have destructive effects when they change from the design values, and both can undergo large changes, particularly with sonar-transducer loads.

The effect of the power factor has been introduced in the preceding section titled "Linear Class B Amplifier Principles" and is shown in Figs. 3 through 7 developed therein. For a specific magnitude of impedance, a particular amplifier is theoretically capable of delivering a specific maximum volt-ampere product. This product is equal to the power when the load has a unity power factor. The actual average power will be, of course, reduced by the power factor.

Unfortunately, this is not the only effect of power factor. From Eq. (7), it can be derived that the dissipation increases from that of a unity-power-factor design by an amount given by the equation:

$$\Delta P_d = \frac{E_{pk} I_{pk}}{C_E C_I} \ (1 - \cos \theta_z). \tag{14}$$

It can be seen from this relationship, therefore, that the maximum output volt-ampere product will have to be reduced in order to reduce the dissipation and keep it below the device limit. This process will result in a twofold reduction in the maximum obtainable output power, first from the reduction in the volt-ampere product, and second from the lower average power developed from the now-reduced volt-ampere product.

The parameter of the load which is usually the most variable is the magnitude of the impedance, hereinafter referred to as load-magnitude. A particular load-magnitude will yield a set of performance curves, like those of Figs. 3 through 7, for the various power factors. Referring to Fig. 3 for unity power factor, it is obvious that an increase in load-magnitude will reduce the current and thus reduce the output power and dissipation, and that a decrease in load-magnitude will increase the output power and dissipation.

If safe operation of the class B amplifier at all signal levels is to be attained, the peak value of the dissipation curve must not exceed the device-dissipation limit. The load-magnitude which causes this condition for unity power factor will then be the optimum resistance load for that particular set of devices.

If clipping is not allowed to occur, any increase in the load-magnitude will reduce the current, and thus reduce both output and dissipation. Therefore, operation in this region of load-magnitudes will be clipping-limited, and, while completely safe for the amplifier, will still result in a reduction in the maximum obtainable output power.

Any decrease in the load-magnitude from the optimum value, however, while theoretically increasing the current and the obtainable output power, will also increase the values of the dissipation curve, and will result in the peak dissipation exceeding the device limits. In order to maintain safe amplifier operation, therefore, it will be necessary, for small reductions in load-magnitude, to confine operations to signal levels that are to the left of the lower, and to the right of the upper, intersections of the dissipation curve shown in Fig. 3 with the device dissipation limit. With further reductions in load-magnitude, safe amplifier operation can be obtained only with signal levels to the left of the curve intersection (less than 0.274 per-unit voltage).

Operation of an amplifier with a slight reduction of load-magnitude from the optimum value in the region to the right of the intersection of the dissipation curve and the device limit requires circuitry to assure that the signal never gets into the region between the left and right intersections. The limits of this area of obtainable outputs will therefore be shown dotted in the subsequent graphs.

There are devices in which the maximum-current capability will be reached before the operating dissipation reaches its limit. When using such devices, it will be necessary to reduce the obtainable output as load-magnitude is reduced in order to remain within the current ratings. This reduction is of the same form as the voltage-limiting reduction.

The effect of load-magnitude, and the voltage, current and dissipation limits, may be graphically shown by plotting the maximum obtainable power as a function of load-magnitude. This has been done in Fig. 10 on a per-unit basis for unity power-factor loads and for devices which are capable of the theoretical maximum efficiency of 78.5 percent. The area of obtainable power of a class B amplifier will then be that area between the voltage and dissipation limits (and the current limit, if applicable). When the reduction in power caused by power factor is applied to the limits plotted in Fig. 10, the result will be the series of curves to the right of and below these limits, as shown in Fig. 11. The current limit indicated on Figs. 10 and 11 is that for the 2N2493 transistor mounted on a water-cooled heat sink. For that transistor and heat sink, the per-unit value of normalized power is 500 watts per pair of transistors.

PRACTICAL APPLICATION AND SUMMATION OF RESULTS

The results obtained in the previous section show graphically how the power-output capability of a theoretical class B amplifier will behave as a function of the load. The behavior of practical amplifiers is obtained by the application of Fig. 3 for the particular device maximum-voltage capability (or efficiency) in question. These results have been plotted for maximum efficiency capabilities of 75, 70, 65, 60, 55, and 50 percent (voltage capabilities of 0.955, 0.891, 0.829, 0.767, 0.701, and $0.639E_{dc}$) and for various power factors in Figs. 12 through 17. These curves show the maximum obtainable output power of practical amplifiers normalized to that output power which is developed at the optimum load-magnitude with a unity-power-factor load in a theoretical amplifier.

The effect of using high crest-factor signals in a class B amplifier is the same as operating with reduced-value sine waves. The effect on dissipation can either be ignored or be a reduction in dissipation and an increase in efficiency. Therefore, to a first approximation, the power capability of any class B power amplifier under any condition of signal or load may be determined by the use of the output-versus-impedance curves of Figs. 10 through 17 to determine the sine-wave average power, and by the application of the multiplication factor for the crest factor of the voltage (Fig. 9) to this sine-wave value. This power capability will then be the device power capability, and ignores circuit losses. The net effect of circuit losses such as transformer efficiency (assuming that the impedance transformation was made ignoring the losses) is to increase the required device power-output capability. For example, with a transformer of 95 percent efficiency, in order to develop one kilowatt in the load, a 1.053-kilowatt amplifier capability from a device standpoint will be required.

To be accurate, when using voltage signals with a large crest factor and non-unity power-factor loads, it is necessary to account for changes in form factor and current crest factor by referring back to the equations. Fortunately, the result of changes in these two factors will normally be an increase in the maximum obtainable power from that figured ignoring them, both in terms of increased average power and of reduced dissipation.

Finally, the results of this analysis do not apply to class AB amplifiers, except when the amount of class A bias is very small, less than two percent of the peak current. Class A bias larger than this will increase the dissipation and reduce the output power, from the standpoint both of the increased dissipation and of the reduced current available for providing output power.

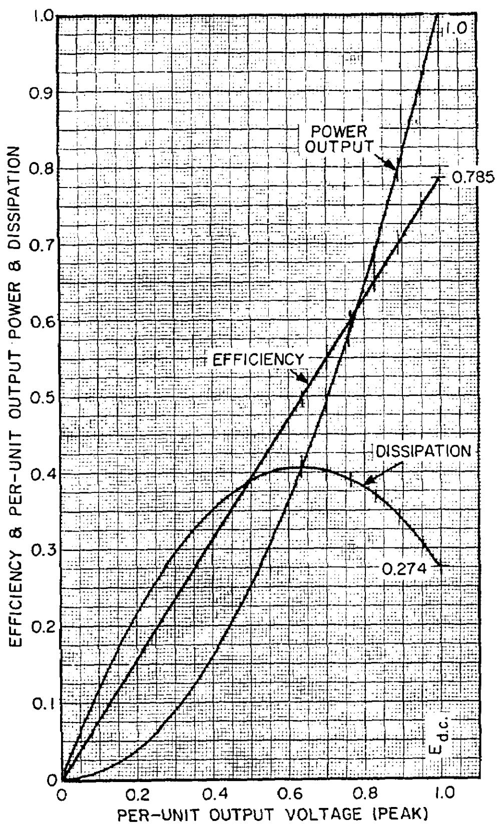


Fig. 3 - Amplifier operation versus output-voltage level, p.f. = 1.0, C_E = 1.414

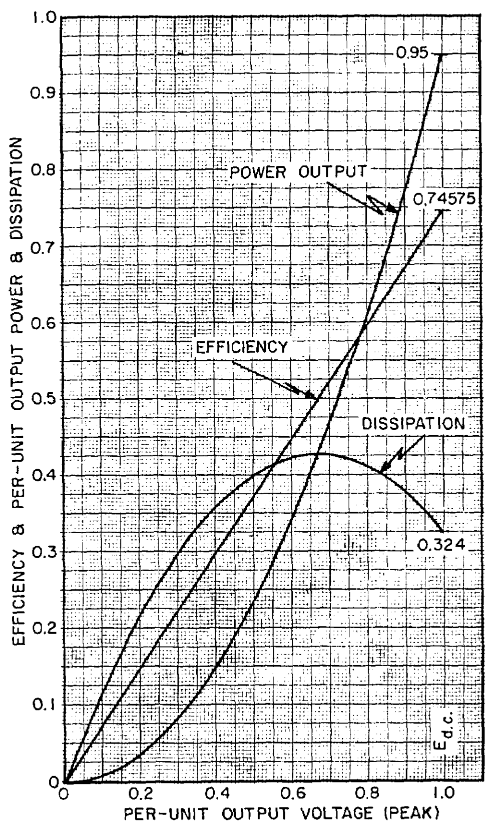


Fig. 4 - Amplifier operation versus output-voltage level, p.f. = 0.95, C_E = 1.414

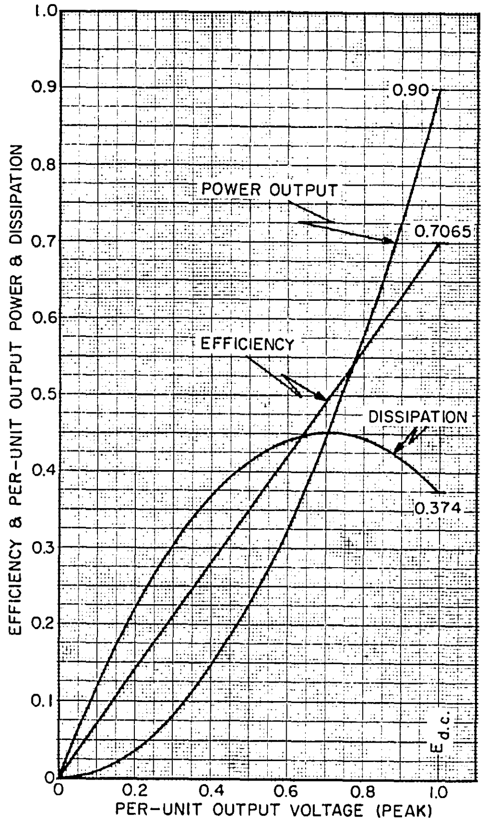


Fig. 5 - Amplifier operation versus output-voltage level, p.f. = 0.9, C_E = 1.414

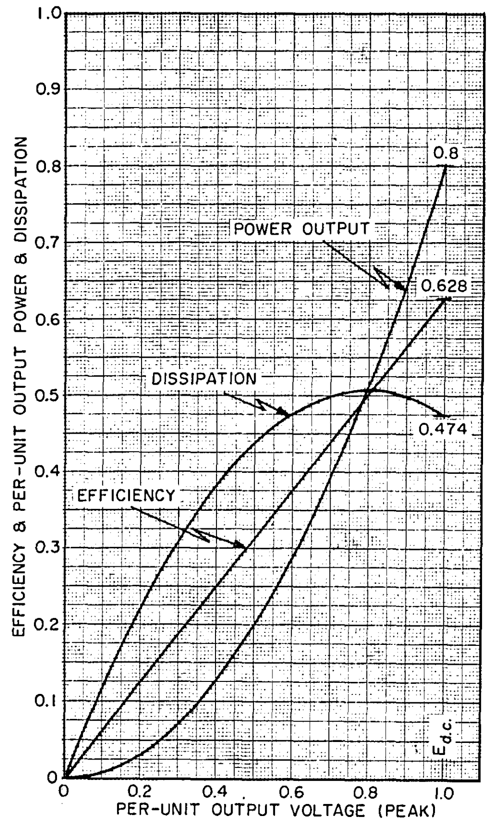


Fig. 6 - Amplifier operation versus output-voltage level, p.f. = 0.8, C_E = 1.414

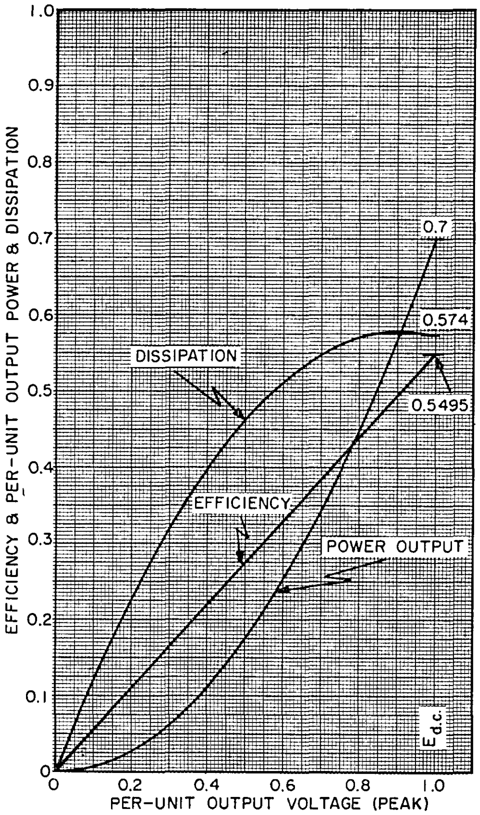


Fig. 7 - Amplifier operation versus output-voltage level, p.f. = 0.7, C_E = 1.414

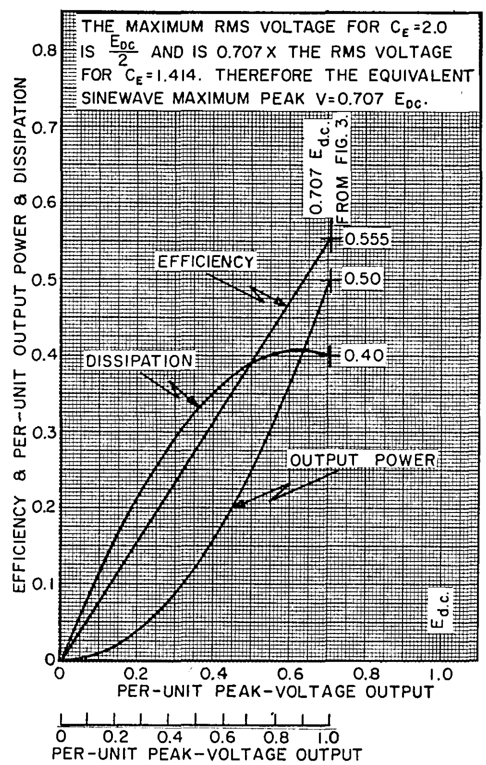


Fig. 8 - Amplifier operation versus output-voltage level, p.f. = 1.0, C_E = 2.0

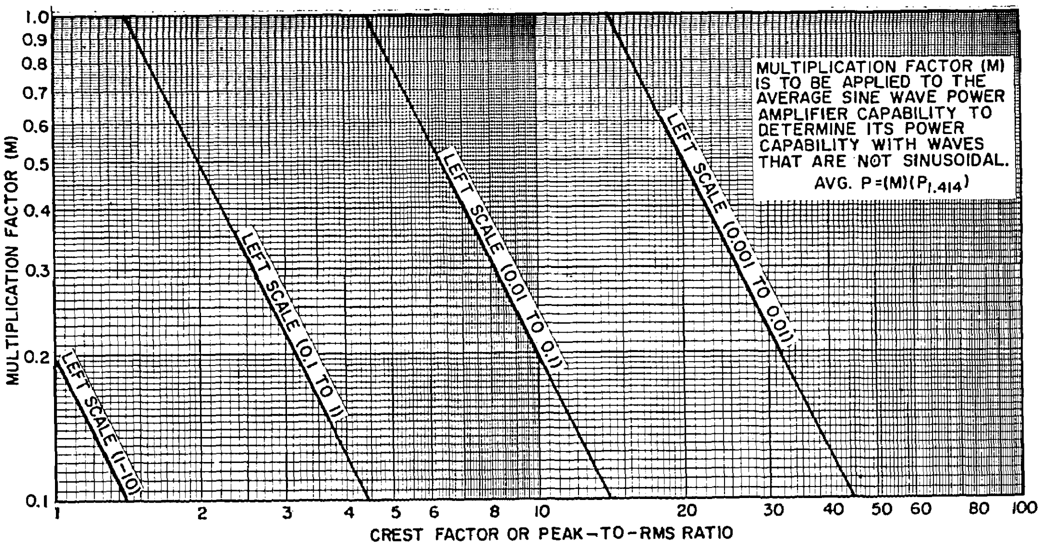


Fig. 9 - Multiplication factor (M) versus crest factor for obtaining average power from sine-wave power

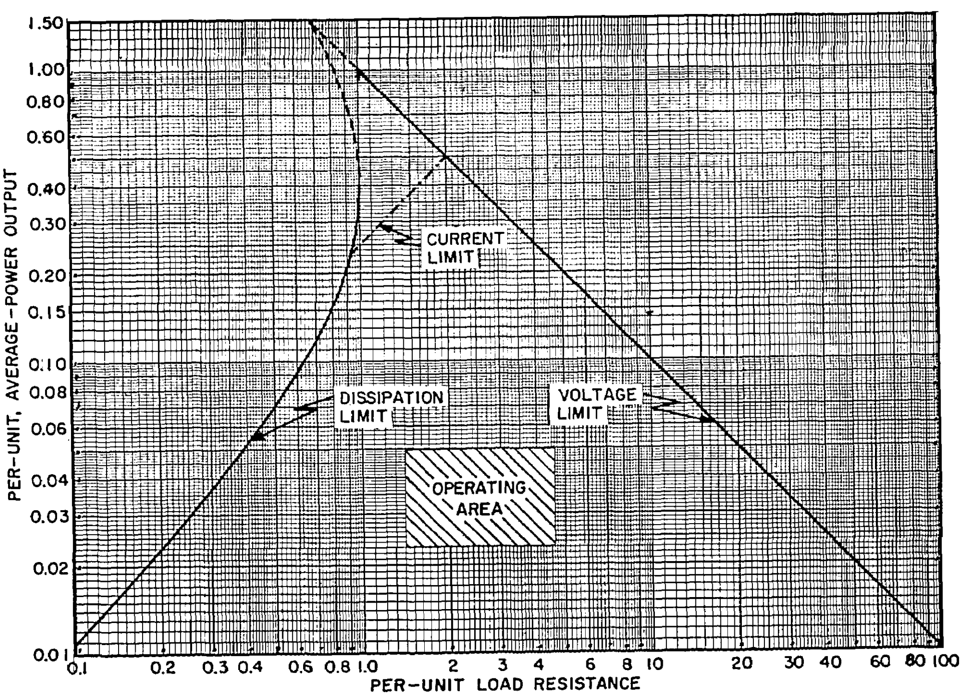


Fig. 10 - Output-power capability versus load resistance, $C_E = 1.414$, p.f. = 1.0

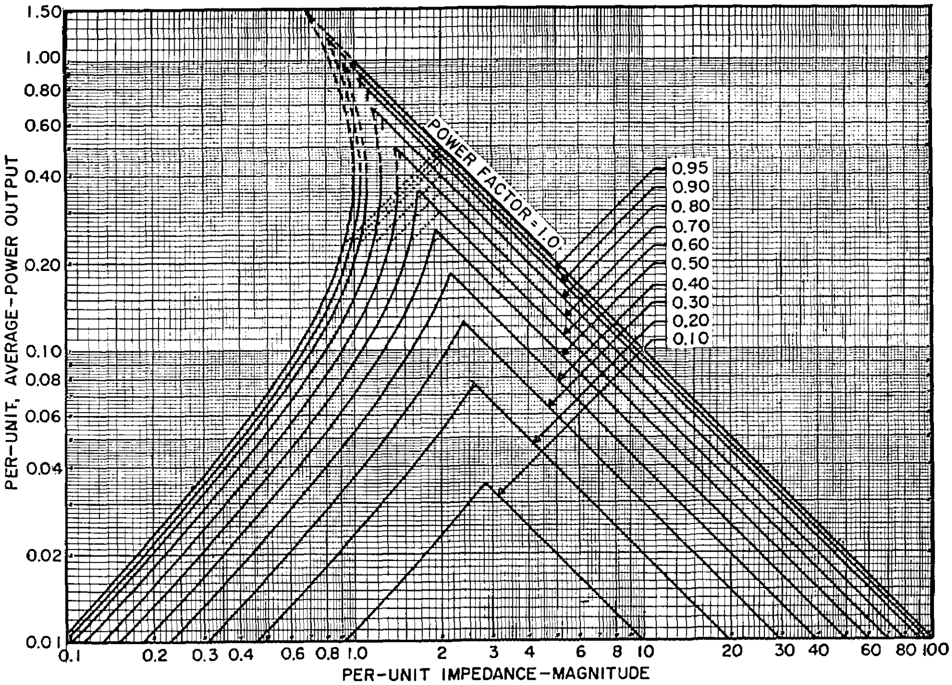


Fig. 11 - Output-power capability versus load impedance and power factor, $C_E = 1.414$

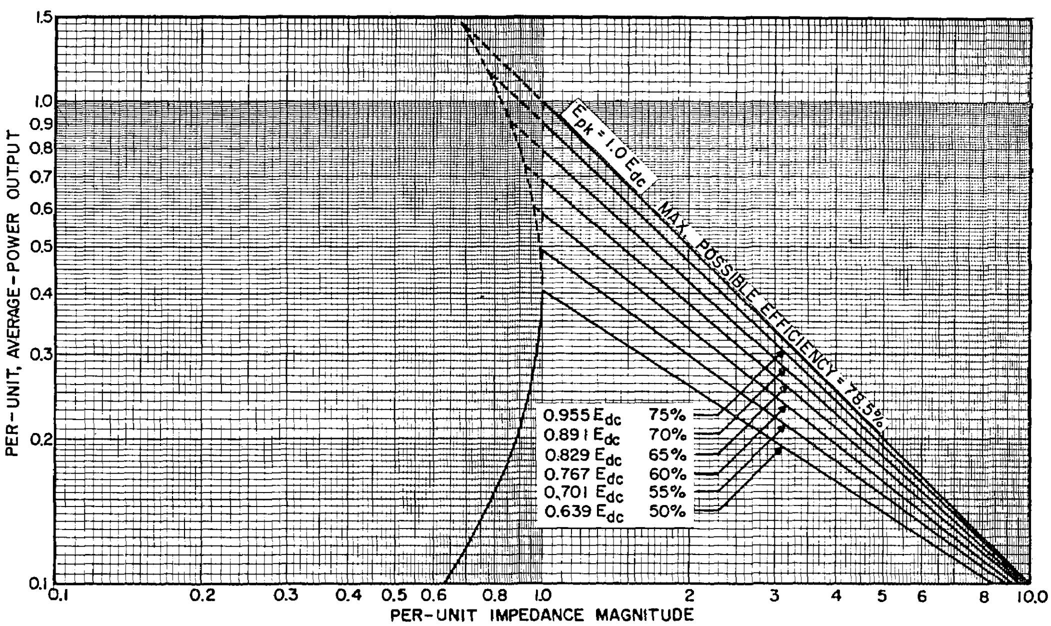


Fig. 12 - Output-power capability versus load impedance and efficiency, $C_E = 1.414$, p.f. = 1.0

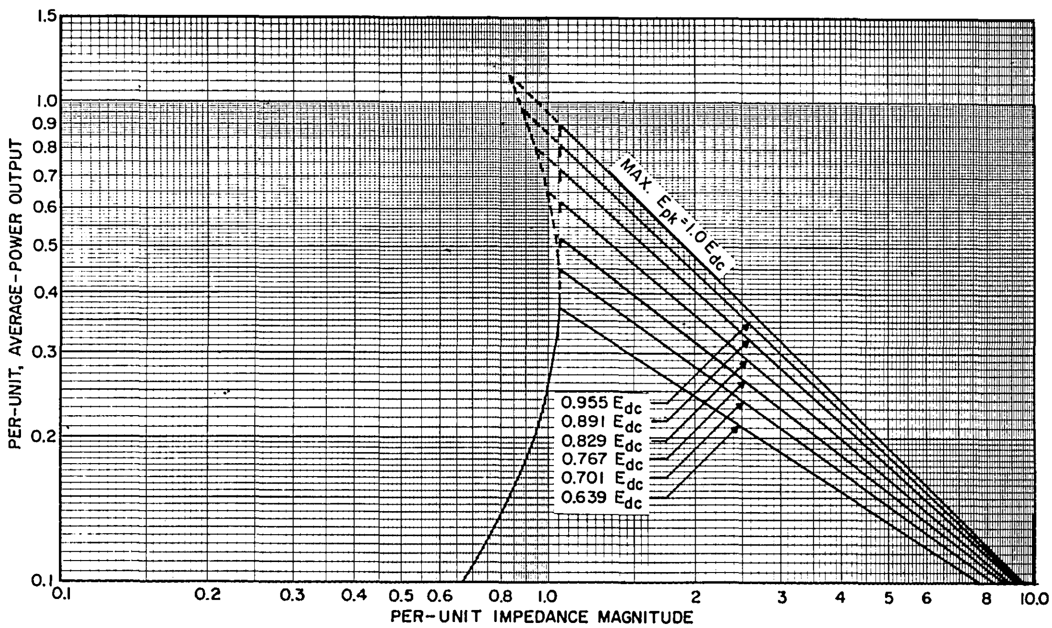


Fig. 13 - Output-power capability versus load impedance and efficiency, $C_E = 1.414$, p.f. = 0.95

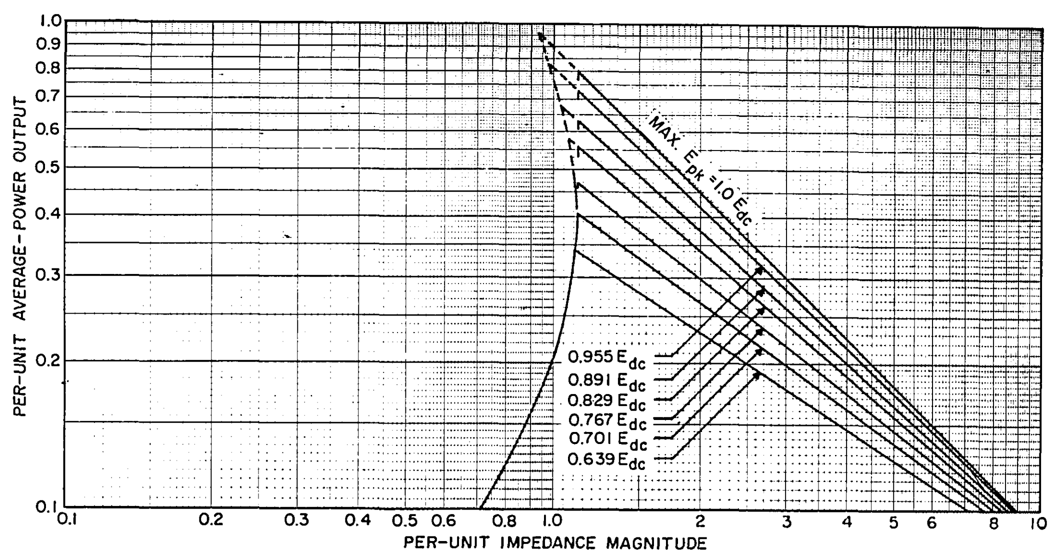


Fig. 14 - Output-power capability versus load impedance and efficiency, $C_E = 1.414$, p.f. = 0.9

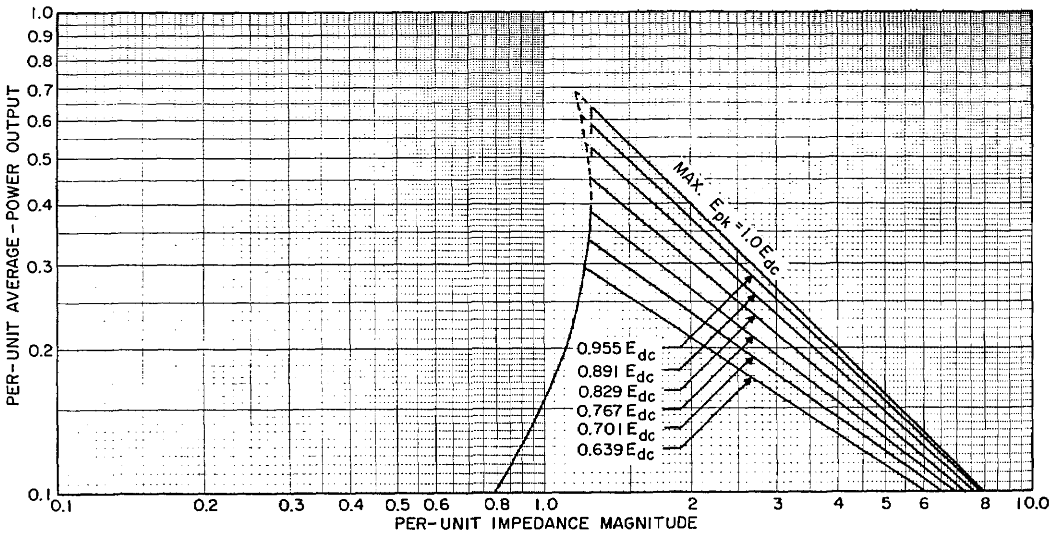


Fig. 15 - Output-power capability versus load impedance and efficiency, C_E = 1.414, p.f. = 0.8

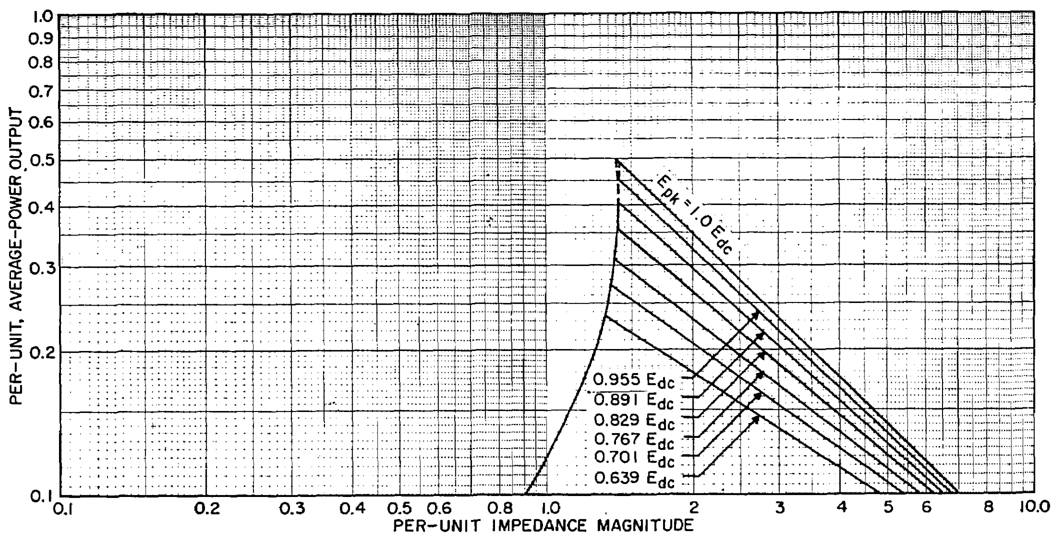


Fig. 16 - Output-power capability versus load impedance and efficiency, C_E = 1.414, p.f. = 0.7

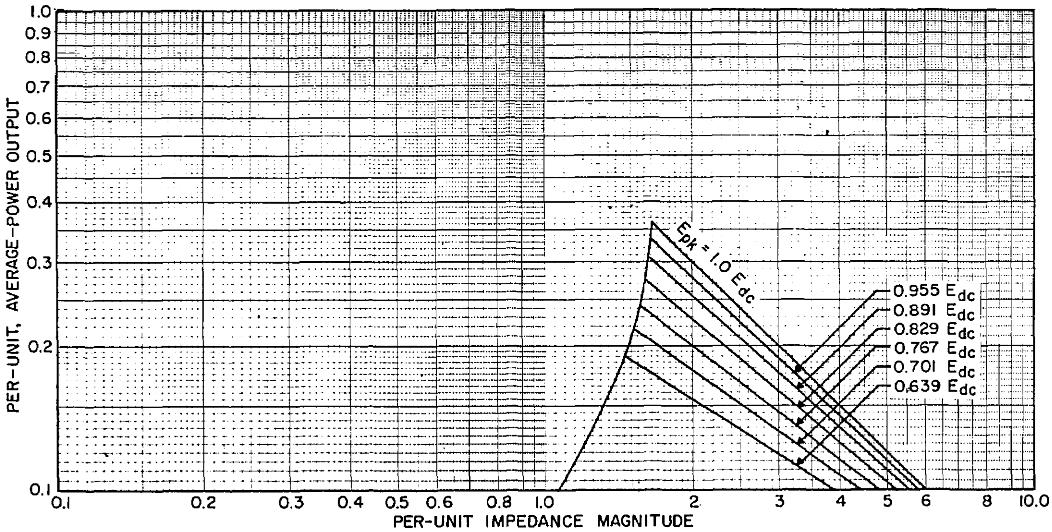


Fig. 17 - Output-power capability versus load impedance and efficiency, $C_E = 1.414$, p.f. = 0.6

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13. ABSTRACT

Large amounts of electrical power at audio frequency are usually provided by some form of class B electronic amplifier. Unfortunately, changes in load impedance and in waveform can result in very large reductions in the output-power capability of such amplifiers.

The design equations for class B amplifiers are developed with respect to impedance and signal waveshape. Manipulation of the equations leads to proof that class B amplifier operation with any signal waveshape can be assumed to be the same as operation with a sine-wave of the same root-mean-square value. Therefore, once the sine-wave capability of a class B amplifier is determined, its capability for other waveshapes is determined by application of a simple derived multiplication factor.

The sine-wave capability of class B amplifiers has been determined and presented in the form of graphs of power versus magnitude of impedance for fixed power factors and device peak-voltage capabilities.

In general, the optimum sine-wave-output capability is determined as the power-dissipation capability of each device multiplied by 4.93, provided the current limit is not exceeded. The actual output capability will be reduced in magnitude by load and signal effects and system efficiency. This reduction is of the order of ten for loads with power factor of 0.7 and impedance swing of 4:1 and for device efficiency of 70 percent and circuit efficiency of 92 percent.

For signals other than sinewaves, the sine-wave average-power capability is then further reduced and is determined, in the worst case, by multiplying the sine-wave capacity by two and dividing by the square of the crest factor.

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Audio Amplifiers Class B amplifiers Analysis Electrical impedance Waveform analysis						

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